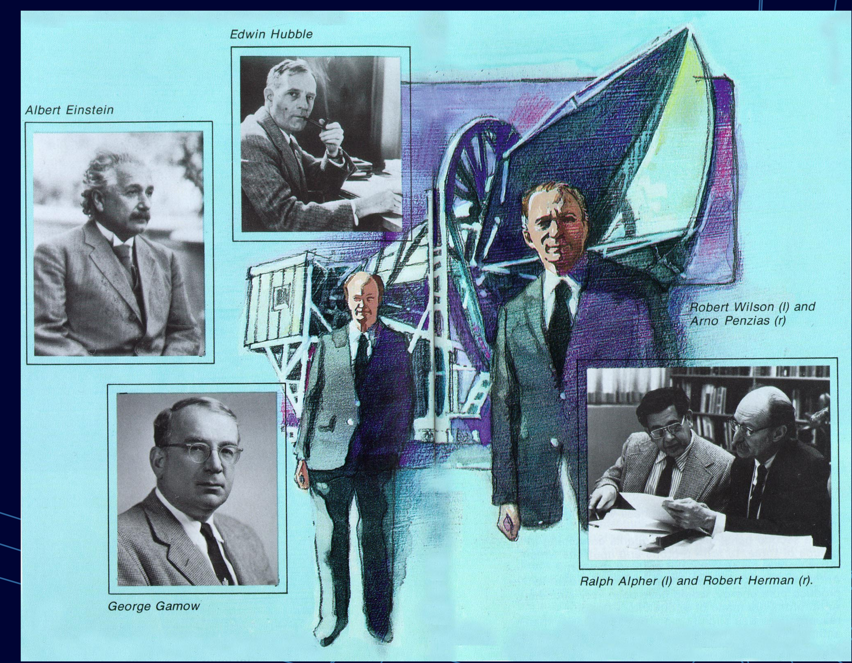
THE DISCOVERY OF THE COSMIC MICROWAVE AND INFRARED BACKGROUNDS

COSMOLOGICAL MILESTONES

The General Theory of Relativity

In 1915 Einstein introduced the General Theory of Relativity. Applying the field equations to the universe as a whole, Einstein discovered that the universe could be either expanding or contracting. In order to keep it stationary, he introduced a cosmological constant, an act he later referred to as his biggest scientific "blunder." The first time varying solutions to Einstein's equations were given by Friedmann in 1922, and in 1927 Lemâitre conducted detailed studies of the dynamical evolution of cosmlogical models with and without a cosmological constant. All this work was done before Hubble's discovery of the expansion of the universe.



The Expanding Universe

In 1929 Hubble published a seminal paper showing that the radial velocities and distances of extragalactic nebulae (galaxies) are related, with more distant galaxies exhibiting larger velocities of recession. The simplest interpretation of this correlation is that the galaxies are receding from each other as part of a universal expansion.

Primordial Nucleosynthesis

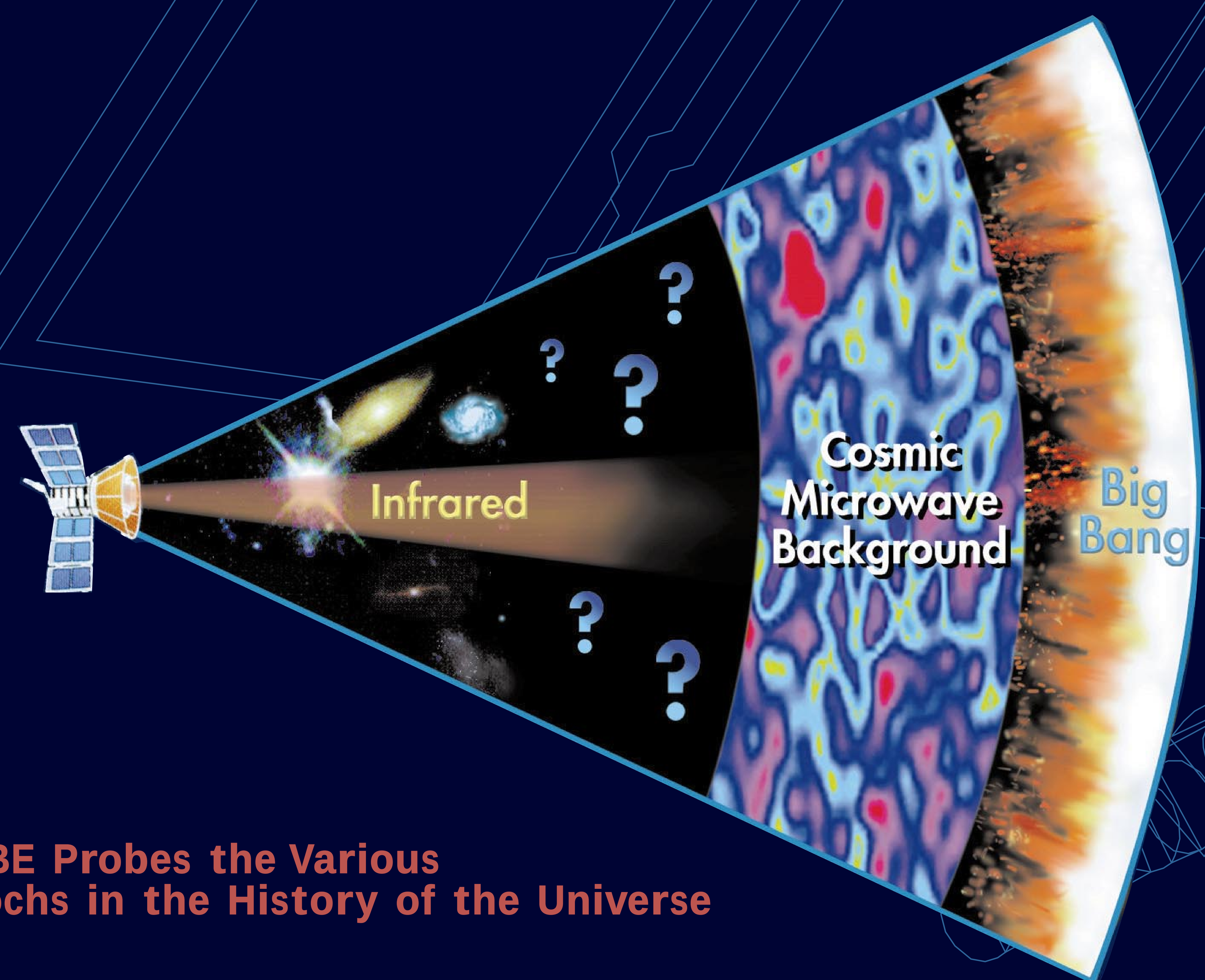
In 1931 Lemâitre, and later, Gamow, concluded that if the universe is currently expanding and cooling off, it must have been much denser and hotter in the past. This model is now referred to as the Big Bang theory for the origin of the universe, a name coined by Hoyle, a bitter opponent of the theory. In the late 1940s Gamow realized the possibility for element formation under such conditions, and together with Alpher and Herman, developed the first primordial nucleosynthesis models. They showed that nuclear reactions could have fused protons and neutrons, creating a universe consisting of 75% hydrogen, 25% helium, and some trace light elements such as deuterium and lithium.

The Cosmic Background Radiation

In the 1950s Alpher and Herman studied the fate of the electromagnetic radiation emitted after the Big Bang. After about 100,000 years, when the universe had cooled enough for electrons and protons to combine and form neutral hydrogen, photons should have been free to expand with the universe. They showed that the radiation should have the spectrum of a blackbody, and should have cooled to a temperature of about 5 K. At this temperature, this relic radiation should have a peak intensity in the microwave/radio region of the spectrum.

Discovery of the Cosmic Microwave Background (CMB)

The cosmic relic radiation was accidently discovered by Penzias and Wilson of Bell Telephone Laboratories in 1964 during their testing of a new and very sensitive microwave antenna. They reported the detection of unexplained excess "noise" in their receiver at 7.3 cm, which came uniformly from all directions in the sky. This uniformity served as an important clue to its extragalactic nature. Their results were predicted and immediately confirmed by Dicke, Peebles, Roll, and Wilkinson from Princeton university.



COBE Probes the Various epochs in the History of the Universe

The Spectral Shape of the CMB

In the Big Bang model, all photons injected into the universe during its first year of expansion thermalize via non-photon conserving reactions, establishing a blackbody spectrum characterized by a thermodynamic temperatute of about 3 K. Subsequent energy releases can distort the spectrum, the shape of the distortion depending on the epoch of energy release.

Photons injected when the universe was still very hot and ionized would have undergone Compton scattering off hot electrons in photon conserving reactions. All photons gain energy, distorting the spectrum, which can be characterized by a Bose-Einstein distribution with a non-zero chemical potential.

Photons injected at a later epoch, when the universe was still ionized but somewhat cooler would have undergone Compton scattering off hot electrons, but some photons will have gained while others may have lost energy. The distortion in the CMB can be characterized by a y-parameter, which measures the effects of the Compton scattering.

Photons injected after the universe recombined would maintain the source spectrum, which is altered en route to Earth by the universal expansion (cosmological redshift), and by interactions with intervening gas and dust.

The Inflationary Universe

Despite its success in explaining the expansion of the universe, the existence of the CMB, and the universal helium abundance, the Big Bang theory fails to explain the smoothness of the background radiation, and the flatness of the universe. The inflationary theory of the universe postulates that between 10^{-34} and 10^{-32} seconds after the Big Bang, the universe underwent an early phase of rapid exponential expansion. This rapid expansion drove sections of the universe that were initially in causal contact and in thermodynamic equilibrium out of causal contact, explaining the observed uniformity of the CMB. The rapid expansion of the universe also expanded a small region that was originally not larger than the size of a baseball to the current size of the universe, explaining its flatness. The inflation was driven by the spontaneous breaking of symmetries in the Grand Unified Theory of elementary particles, and took place at very high energies (10^{14} GeV). Inflation also predicts that the universe should be filled with dark matter, and the spectrum of the primordial density fluctuations that gave rise to the structures seen in the present universe.

The Spatial Variations in the CMB Intensity

The universe shows a great degree of structure. Galaxies seem to be distributed in filamentary lines, in clusters, and even in superclusters. A major problem in the Standard model of the Big Bang is to reconcile the actual structure of matter in the universe with the seeming uniformity of the CMB. In the Cold Dark Matter (CDM) model for the formation of cosmic structure, galaxies are formed in a hierarchical fashion from the merger of initially small units into the larger forms observed today. The first cosmic structures formed from initial density perturbations in the early universe, which grew and collapsed under the effect of gravity. The presence of these density perturbations should have left its imprint on the intensity distribution of the CMB. In fact, the apparent uniformity of the CMB up to 1 part in 10,000 challenged early theories for structure formation, which predicted significantly higher intensity variations.

Nucleosynthesis in Stars and the Cosmic Infrared Background

The efforts of Alpher, Herman, and Gamow, as well as subsequent efforts by Fowler, Wagoner, and Hoyle, failed to produce any elements heavier than lithium by Big Bang nucleosynthesis. The problem arose from the lack of any stable element at mass 5 and 8. With the advances in nuclear physics it became possible to measure and calculate nuclear reaction rates relevant to astrophysical processes. In 1939 Bethe described the hydrogen burning process in stars, and in 1957 Burbidge, Burbidge, Fowler, and Hoyle presented a detailed description of the stellar nuclear processes, the astrophysical settings required to provide energy production in stars, and the relative abundances of the elements in nature. The energy liberated in these nuclear reactions eventually makes its way to the surface of the star, from which it is radiated into space at ultraviolet and visible wavelengths. The cosmic expansion will shift the stellar and galactic spectra to near infrared wavelengths. Furthermore, a significant fraction of the emitted starlight can be absorbed and reemitted by intervening dust at far infrared wavelengths. We therefore expect a significant fraction of the energy released in the formation of the elements to appear at infrared wavelengths.

THE LEGACY OF THE COSMIC BACKGROUND EXPLORER

The Mission Objectives

To put cosmology on a solid observational footing, a new experiment was needed. To this end, NASA launched, on November 18 1989, the Cosmic Background Explorer (COBE) Satellite, the first satellite soley dedicated to cosmological studies. COBE carried three instruments: The Far Infrared Absolute Spectrophotometer (FIRAS, led by John Mather and Rick Shafer), dedicated to the measurement of the temperature and spectral shape of the CMB; the Differential Microwave Radiometer (DMR, led by George Smoot and Charles Bennett), dedicated to measure the spatial variations in the intensity of the CMB at select frequencies; and the Diffuse Infrared Background Experiment (DIRBE; led by Michael Hauser and Tom Kelsall), dedicated to study the energy release from the first stars and galaxies in the universe by searching for the cosmic infrared background.

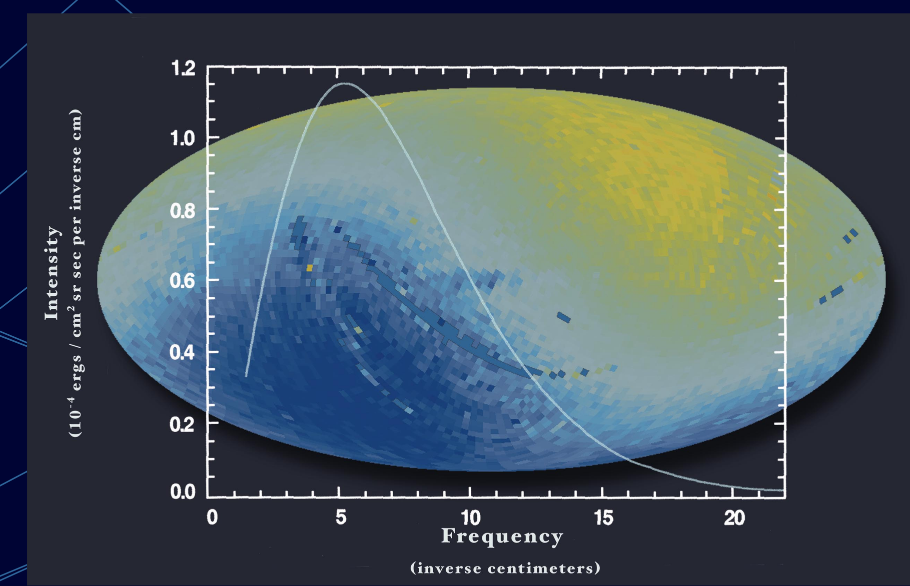
The CMB Spectrum and its Dipole

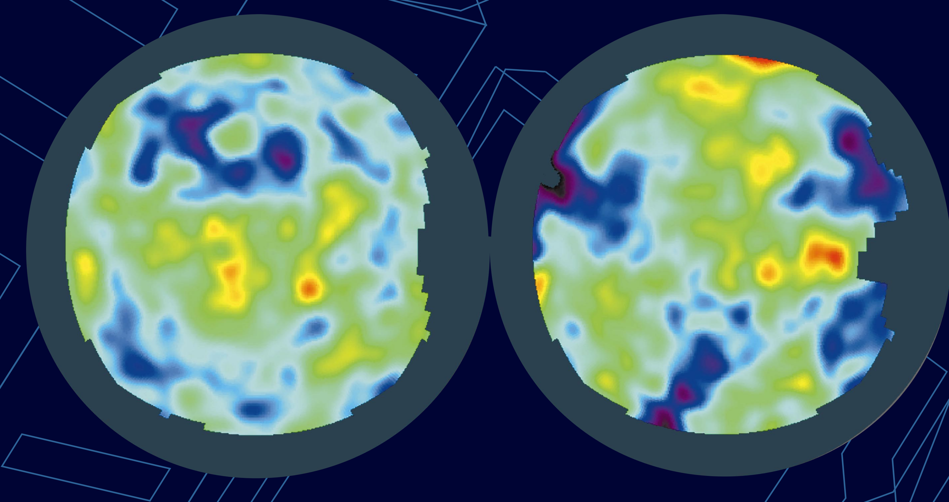
The FIRAS instrument measured the spectrum of the CMB from 1 to 100 cm^{-1} (wavelengths from 100 to 10,000 microns). It operated at a temperature of 1.5 K inside a liquid helium cryostat and was designed to measure any deviations of the CMB from a blackbody reference spectrum to an accuracy of 0.1% of the peak spectrum. The results showed that the CMB spectrum matches that of a blackbody with a temperature of 2.725 plus or minus 0.002 K to within 50 parts per million of the peak intensity of the CMB.

This remarkable agreement of the CMB spectrum with that of a blackbody is a major confirmation of the Big Bang theory for the origin of the universe, setting strict upper limits on the contribution of various energy sources to the energy budget of the universe at various epochs. The FIRAS observations also puts very strong constraints on "non-standard" cosmological models, such as the Steady State model, advocated in 1948 by Bondi, Gold, and Hoyle, or models in which "tired" light is responsible for the observed redshift of galaxies, instead of cosmological expansion.

The CMB is not exactly uniform in all directions. There is a large-scale anisotropy caused by the Sun's motion relative to the CMB. Both the FIRAS and the DMR measured the intensity of the dipole, and the Sun's velocity and direction of motion with respect to the CMB, with very high accuracy. The results show that the Sun is moving with a velocity of 368.9 km/sec toward galactic coordinates $l=264.26^{\circ}$ and $b=48.22^{\circ}$. Because of this motion, the temperature of the CMB is 3.353 mK higher in one direction, and lower by exactly the same amount in the opposite direction.

The figure on the right depicts the cosmic microwave background spectrum, superimposed on the map of the dipole. The CMB therefore defines a cosmic frame of rest with respect to which we can measure our velocity through the universe. The solid curve shows the expected intensity from a single temperature blackbody, as predicted by the hot Big Bang theory. The FIRAS data were taken at 34 positions equally spaced along this curve. The FIRAS data match the curve so exactly, with error uncertainties less than the width of the blackbody curve, that it is impossible to distinguish the data from the theoretical curve. These precise CMB measurements show that at least 99.994% of the radiant energy of the universe was released within the first year after the Big Bang itself, setting stringent constraints on all subsequent energy releases.





The Large-scale Anisotropy of the CMB

The DMR instrument was designed to map out any spatial variations in the intensity of the CMB at the frequencies of 31, 53, and 90 GHz and an angular scale of 7°. Maps constructed from data collected over the 4 years of the COBE mission achieved sensitivity levels better than one part in 100,000 of the peak CMB intensity. The figure on the left depicts the distribution of the CMB intensity relative to the CMB temperature after the removal of the dipole. The map shows significant variations in the intensity (temperature) over the sky. These variations map out the seeds of the initial density fluctuations that gave rise to the galaxies and clusters of galaxies seen today.

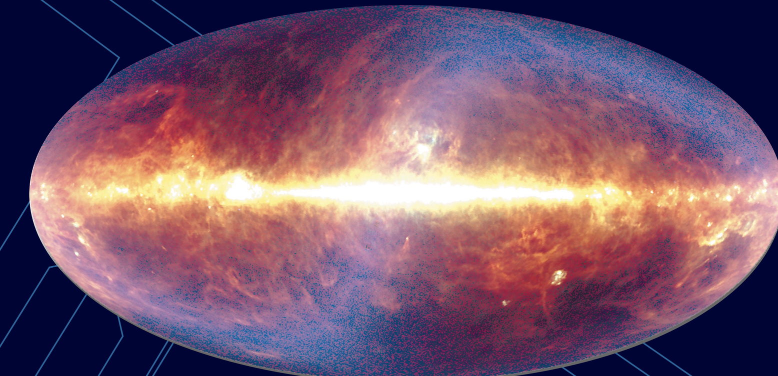
In adiabatic models for the evolution of density fluctuations, radiation and matter are tightly coupled, and hotter regions on the map represent regions of higher matter density. On route to Earth photons that came from these regions lost a fraction of their initial energy (temperature) since they had to climb out of a deeper potential well, compared to photons coming from other directions. So the observed temperature fluctuations actually trace out the seeds of the primordial density fluctuations in the universe.

Inflation predicts the spectrum of these density fluctuations, but not their amplitude. The DMR measurements provide an important normalization point for the amplitude of the large-scale density fluctuations, and therefore make definitive predictions about their amplitudes on smaller scales. The measured large-scale amplitude also provides important support for the existing theory of structure formation. In this theory, the structures observed today formed by gravitational collapse and clustering, instead of explosive or turbulent events in the early universe. However, Cold Dark Matter, consisting of yet undetermined massive relic particles and comprising about 94% of the mass of the universe, is needed to expedite the collapse of these primordial density fluctuations, and cluster them into the galaxies and groups of galaxies we see today.

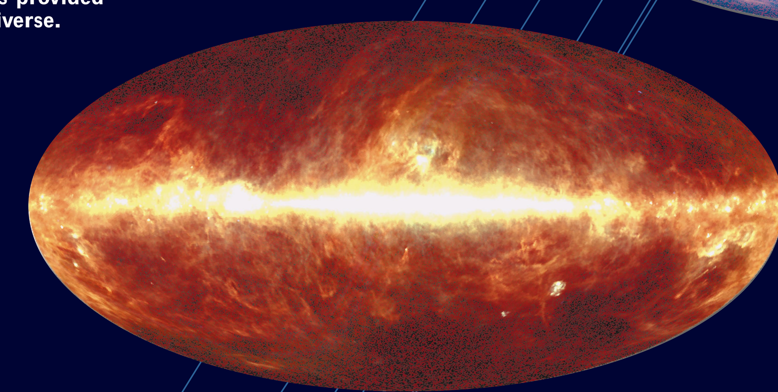
The figure on the left is the DMR "Map of the Early Universe". This false color image shows the tiny variations in the intensity of the CMB measured in the 4 years of COBE observations. The blue and red spots in the image correspond to regions of higher and lower CMB intensities, respectively, and trace the "fossilized" relic distribution of the primordial density fluctuations that gave rise to the observed structure of matter seen today.

The Cosmic Infrared Background

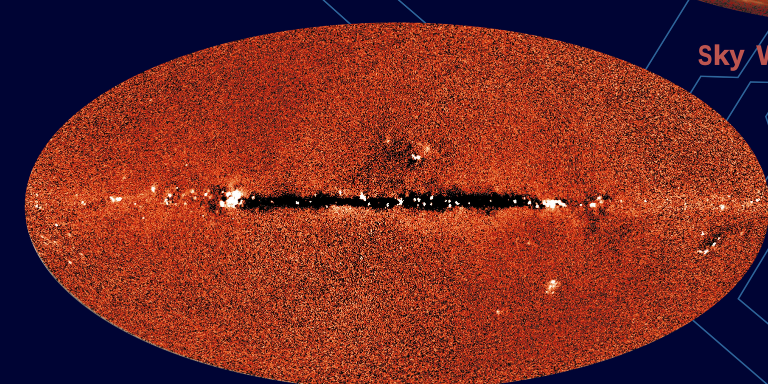
The DIRBE instrument was designed to conduct a systematic search for the Cosmic Infrared background (CIB), the cumulative emission from all pregalactic, protogalactic and evolved galactic systems since the decoupling of matter from the CMB. The DIRBE surveyed the sky in 10 photometric bands ranging from 1.25 to 240 microns. At these wavelengths foreground emission from interplantary dust in our solar sytem, and infrared emission from stars and dust in our Milky Way galaxy dominate the emission in the various wavelength regions. Careful modeling of these foreground emissions was required to subtract the infrared glow of these foreground objects in order to derive the extragalactic component of the emission. The figure below illustrates the foreground emission subtraction process that resulted in the detection of the CIB at 240 microns. The CIB was also detected at 140 microns, and at 240 to 1000 microns by the FIRAS instrument as well. The integrated light intensity detected by the DIRBE and FIRAS instruments in the 140 to 1000 micron region is consistent with the energy release expected from nuclear energy sources and consitutes about 20 to 50% of the total energy released in the stellar synthesis of helium and heavier elements throughout the history of the universe. In addition, the DIRBE and FIRAS results provided important constraints for the star formation history of the universe.



Observed Sky



Sky Without Interplanetary Dust Emission



Extragalactic Background

The group of three images shown above depicts the steps taken by the DIRBE Team in deriving the cosmic infrared background. The map at the top is a false color image showing the observed sky brightness at 60 (blue), 100 (green) and 240 microns (red). The bright yellow horizontal band across the middle of the map corresponds to the emission from interstellar dust in the plane of the Milky Way galaxy (the center of our galaxy is in the middle of the map). The wispy structure above and below the plane represents the emission from dust in cool Galactic "cirrus" clouds. The blue S-shaped figure represents the emission from interplanetary dust in the solar system. The middle map is a 60-100-240 micron false color image of the sky after the subtraction of the interplanetary dust contribution to the emission. Emission from interstellar dust in the Milky Way now dominates the image. After the removal of this emission component, the residual emission should be the uniform Cosmic Infrared Background. The bottom image represents the residual emission at 240 microns. The dark line across the center is an artifact from the removal of the Galactic emission.

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